Integrated modelling of the influence of urbanization and climate change on river water quality

Modélisation intégrée de l'influence de l'urbanisation et du changement climatique sur la qualité des eaux de rivière

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RÉSUMÉ

Le changement climatique est l'un des phénomènes ayant le plus d'impact sur les caractéristiques hydrologiques et environnementales des bassins versants naturels. Afin de mieux contrôler la qualité des eaux naturelles, il faut tenir compte de ces facteurs, de même que les facteurs anthropiques peuvent augmenter ou diminuer l'effet des modifications climatiques. Ce qui manque jusqu'ici dans ce domaine est une analyse détaillée et généralisée de ces impacts environnementaux à une échelle relativement réduite. L'usage d'une approche holistique est également exigé par la directive cadre européenne 2000/60 qui demande une analyse intégrée pour la gestion des bassins versants afin de répondre aux objectifs environnementaux et écologiques. Cette communication se penche donc sur cette problématique. Afin de quantifier l'impact des facteurs anthropiques (l'urbanisation, la population, la demande en eau, etc.) et des changements climatiques sur la qualité de l'eau des rivières, un modèle intégré existant a été utilisé pour prévoir le débit et la qualité des eaux dans les systèmes d'égout, les stations d'épuration et les milieux aquatiques. La qualité de l'eau de rivière est alors utilisée pour limiter l'ampleur de nouveaux aménagements afin de ne pas dépasser les seuils de qualité des eaux déterminés par les normes européennes. L'analyse a été appliquée à un bassin versant expérimental, le bassin partiellement urbanisé de Nocella, qui se situe dans le nord-ouest de la Sicile, en Italie.

ABSTRACT

Climate change is one of the most important drivers modifying the hydrologic and environmental characteristics of natural catchments. When dealing with the quality of natural waters, these factors should be weighed up against anthropogenic factors that may increase or decrease the effect of climatic modifications. However, a detailed and more generalised analysis of such environmental impacts at a relatively small scale is currently lack. This paper aims to fill this gap. The use of a holistic approach is also required by the EU Water Framework Directive, which prescribes integrated analysis for river basin management in order to meet environmental and ecological objectives. In order to quantify the impact of anthropogenic (urbanization, increased population, higher water demand, etc.) and climatic changes on river water quality, an existing integrated urban wastewater model was used to predict water flow and quality in the sewer system, treatment plant and receiving water body. The impact on combined sewer overflow discharges, treatment plant effluent, and within the river at various reaches is analysed by 'locating' a new development on an urban catchment. River water quality is used as a feedback mechanism to constrain the scale of the new development within different thresholds in order to ensure compliance with water quality standards. The analysis has been applied to an experimental natural catchment: the Nocella catchment, which is a partially urbanised natural catchment located in the north-western part of Sicily, Italy.

KEYWORDS

Integrated system modelling; receiving water body, uncertainty analysis; water quality

1 INTRODUCTION

New housing areas and the increase of urban population are ubiquitous features of modern life in the developing and developed world alike, built in response to rising social, demographic and economic pressures. Inevitably, these factors will have an impact on the environment around them and they will add to the impacts provided by the modification of climate with specific regards to precipitation. Empirical evidence confirms the close relationship between urbanization, climate change and ambient water quality (Franczyk and Chang, 2009). In the Mediterranean area, the increased frequency of intense rainfall events, the general reduction of annual precipitation, the extension of urban areas and the increased pressure of population of receiving water bodies have to be analysed together in order to evaluate their global impact.

In literature, the integration of climatic and anthropogenic factors has been addressed in several studies, aiming to guide changes toward the sustainable management of water resources (IUCN et al., 1980; UN, 1992), to balance human nneds and environmental preservation in natural water resources exploitation (UNESCO, 1987; Bouwer, 2002), to assess the possible combination of human and natural factors on natural water quality (UNESCO, 1987; Doll et al., 2003; Giupponi et al., 2006).

The introduction of Global Change as the combination of anthropogenic and climatic factors is present in the European Water Framework Directive (European Commission, 2000), clearly demanding new approaches for dealing with the management of natural water resources, considering the variability of natural and social boundary conditions. Compliance with the Directive can be reached by integrated assessment and management, multi-objective decision making and the involvement of human actors and stakeholders (Pahl-Wostl, 2007; Jakeman and Letcher, 2003; Jakeman et al., 2006; Letcher et al., 2007).

The above-mentioned approaches are mainly focused on natural water as a resource to be sustainably exploited, but a detailed and more generalised analysis about the environmental impact of Global Change is still lacking at a relatively small scale. Coupled hydrological and water quality simulation tools, taking socio-economic processes into account is still a challenging task. In particular, systems that aim at evaluating impacts of climatic change on long-term temporal scales cannot be based on the assumption that infrastructure, economy, demographics and other human factors remain constant while physical boundary conditions change. Therefore, any meaningful simulation of possible future scenarios needs to enable socio-economic drivers to be analysed together with climatic changes.

The aim of this paper is to quantify the impact of urbanization and social changes together with climate change on river water quality within an integrated system modelling perspective. To conduct the impact analyses, an existing integrated urban wastewater model was used to predict water flow and quality in the sewer system, treatment plant and receiving water body. As the modelling analysis is affected by inherent uncertainty due to model complexity and calibration, the analysis was performed considering the effect of such uncertainty on results reliability.

The analysis has been applied to an experimental catchment near Palermo (Italy): the Nocella catchment that is an highly urbanised natural catchment located in the north-western part of Sicily, Italy. The river receives wastewater and stormwater from two urban areas (70 ha and 45 ha respectively) drained by combined sewers. Each of them is connected to a WWTP protected by CSO devices. Five river reaches have been simulated characterised by the most relevant concentrated and diffuse polluting sources. The principal monitoring station (Nocella a Zucco) is located 6 km upstream the river mouth with a catchment area of 56.6 km^2. Other monitoring points were located along the river upstream and downstream of the two WWTP and at the outlets of urban sewer systems.

2 MATERIAL AND METHODS

2.1 The analysis of climate change

In recent decades, many natural areas have experienced modifications to local rainfall characteristics concerning the annual number of rainfall events, their average volume and the frequency of intense rainfall events. Many authors have claimed the presence of a significant increasing tendency in high intensity rainfall (De Michele et al., 1998; Brath et al., 1999; Kamaguchi et al., 1999). For urban drainage systems, these changes can have a strong impact on flooding and especially on CSO discharges.

De Michele et al.(1998) have estimated critical design storms, using 90 years of continuous data collected in four northern Italian cities and fitting the annual maxima from historical records, thus assessing the progress of the design storm over time. The results show the presence of a significant increasing trend in the critical design storm, starting in the years around 1940. Furthermore the estimation of the critical design storm using all the data shows that the longer the sample sizes of historical data, the lower is the bias in the critical design storm induced by non-stationarity. Kamaguchi et al.(1999) analysed the rainfall records of a Yokohama local weather station in order to investigate trends in short-term rainfall. These analyses showed that the number of short duration rainfalls and the average of unit time intensity and 5-minute intensity was increasing. Furthermore the probable rainfall intensity estimated from recent data was higher than that from the data of the previous 20 years.

More recently, Aronica et al. (2002) quantify changes in the rainfall regime of the metropolitan area of Palermo (Italy), nearby the natural catchment adopted in the present study, which in a few decades has completely modified its natural environment. A preliminary analysis of the total annual rainfall depths highlighted a global reduction in annual precipitation. However, the examination of annual maximum rainfall indicates a global increase of rainfall intensities.

In accordance to the methods proposed by cited literature, the analysis of climatic trend has been investigated by focusing on intense rainfall events that have perhaps the most relevant impact on urban polluted discharges.Rainfall data have been collected for all the raingauges available inside and nearby the analysed natural catchment. Several rainfall intensity – duration – frequency (IDF) curves have been extrapolated on the bases provided by sub-samples of available data selected by means of a moving temporal window of 20 years. In the study, the monomial form of the IDF curve has been used:

$$h = ad^{n} \tag{1}$$

$$i = ad^{(n-1)} \tag{2}$$

where h and i are respectively the average rainfall depth and intensity for a specific rainfall event duration d and return interval. The parameters a and n represent the scale and the shape of IDF curve and depend from the analysed raingauge and adopted return interval Tr. By means of such analysis, the temporal trend in the IDF curves parameters was assessed by means of historical data and used for making the forecast of the future trend on the intensity of rainfall events with a specified return interval.

2.2 The analysis of socio-economic change

Among the anthropogenic factors that can affect receiving water body (RWB) quality, the modification of population, urban impervious area and water supply represent the most relevant drivers that may affect dry weather and wet weather discharges from urban areas to the RWB (Novotny, 2003). Socio-economic change was mainly connected to these factors, neglecting other aspects that can be difficultly predicted such as water sector technological changes or consumer expectation and social behaviour.

Population and water supply directly affect dry weather flows in the sewer system (SS) and consequently the treatment efficiency of waste water treatment plants (WWTP). The variation of urban impervious area affects wet weather runoff delivered to the SS, which usually is not upgraded to follow the extension of urbanised catchment. For this reason the increase of the urbanised area has the consequence of the increased frequency in CSO polluting spill volumes and loads that has to be considered for evaluating the impact of socio – economic change on RWB quality state.

The analysis of these drivers was analysed by collecting data about the urban areas in the catchment and their population for the annual censuses since 1960. Data has been fitted by a regression law selected by minimising the root square mean error between the measured data and the regression law. Each of the three variables was interpolated by a different regression law as it will be better detailed in the following paragraphs.

2.3 The integrated model

The system was modelled employing a bespoke integrated model developed during previous studies (Mannina, 2005). The structure of the adopted model will be briefly described here, as the cited literature can be referenced for a more detailed description of the chosen algorithms.

In brief, the model is able to estimate both the interactions between the different systems, i.e. SS, WWTP, Combined Sewer Overflow (CSO), and RWB, and the impacts, in terms of water quality, that urban storm water has on the RWB. The modelling structure can be adapted to the specific application by removing or adding sub-models or parts of them, such as the Storm Water Tank (SWT), or the Combined Sewer Overflow (CSO), as depicted in Figure 1. Such an integrated system is made up mainly of three sub-models:

- the rainfall-runoff and flow propagation sub-model, which evaluates the qualitative-quantitative features of the storm water;
- the WWTP sub-model, which is representative of the treatment processes;
- the receiving water body sub-model, which simulates the pollution transformations inside the water body.

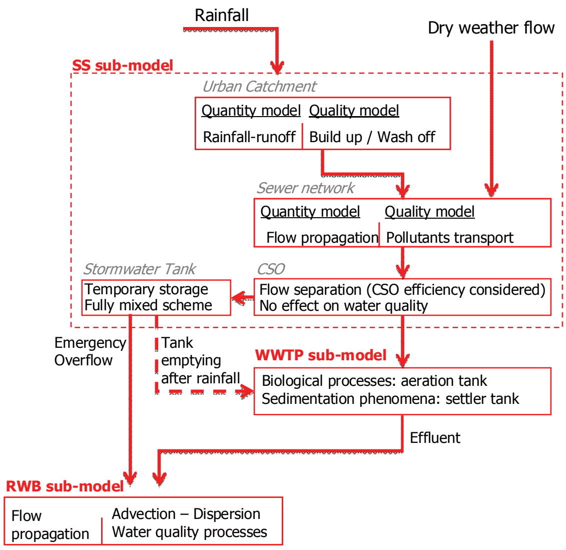


Figure 1: Schematic overview of the different sub-models, analysed processes, and interconnections.

The first sub-model describes the physical phenomena that occur both in the catchments and in the sewers, and allows the user to define the hydrograph and pollutograph in the sewer. For the assessment of the latter, particular attention was given to the sediment transformation in sewers, considering their cohesive-like behaviour linked to organic substances, and to the physical-chemical changes during sewer transport (Mannina and Viviani, 2010a). The urban sewer system was modelled considering two reservoirs and one linear channel; the main physical-chemical phenomena that take place during both dry and wet periods were taken into account. Specific attention was given to the antecedent dry weather period (ADWP) that is responsible of the first flush event.

As stated above, the second sub-model is aimed at the analysis of WWTP. In particular, this sub-model simulates the behaviour of the activated sludge tank and the secondary sedimentation tank. In the activated sludge tank model, the equations derived from Monod’s theory were used to describe the removal of BOD and NH_4 (Monod, 1942). The sedimentation tank was simulated using the modelling approach of Takács et al. (1991). In particular, the model predicts the solids concentration profile in the settlement tank by dividing the settlement tank into a number of layers of constant thickness, and by performing a solids balance for each layer. The third sub-model assesses RWB discharges and water quality. More specifically, the modelling approach has been focused on rivers characterised by few field data and ephemeral characteristics (i.e. rivers characterised by a long dry season and intense flow for short periods following precipitation). This latter aspect is relevant since the phenomena generally involved in the evaluation of the RWB quality state play a different role with respect to the perennial streams commonly presented in the literature (Mannina and Viviani, 2010b). Ephemeral rivers are also found frequently in Mediterranean areas that are characterised by semi-arid climates. Due to the highly non – stationary conditions typical of the ephemeral streams, a dynamic model was employed for the propagation of the flow in the river. The advection-dispersion equation was implemented to address the water quality phenomena.

2.4 The adopted case study and the monitoring campaign

The analysis was applied to a complex integrated catchment: the Nocella catchment that is an urbanised natural catchment located nearby Palermo in the north-western part of Sicily (Italy). The entire natural basin is characterised by an area of 99.7 km^2, and has two main branches that flow primarily east to west. The two main branches join together 3 km upstream from the river estuary. The southern branch is characterised by a smaller elongated basin, and receives water from a large urban area characterised by relevant industrial activities partially served by a WWTP, and partially connected directly to the RWB. The northern branch was monitored in the present study (Figure 2). The basin closure is located 9 km upstream from the river mouth; the catchment area is 66.6 km^2. The catchment end is equipped with a hydro-meteorological station (Nocella a Zucco). The river reach receives wastewater and stormwater from two urban areas (Montelepre, with a catchment surface equal to 70 ha, and Giardinello, with a surface of 45 ha) drained by combined sewers. Montelepre sewer system serves 7,000 inhabitants, and it is characterised by an average dry weather flow equal to 12.5 l/s (water supply 195 l/capita/d), and an average dry weather BOD concentration of 223 mg/l. Giardinello population is 2,000 inhabitants, and it has an average dry weather flow equal to 2.5 l/s (water supply 135 l/capita·d) and an average dry weather BOD concentration of 420 mg/l. The calculated BOD unit loading factors for the two urban catchments are 35 and 45 g/capita/d for Montelepre and Giardinello, respectively. Each sewer system is connected to a WWTP protected by CSO devices. The WWTPs are characterised by simplified activated sludge processes with preliminary mechanical treatment units, an activated sludge tank, and a final circular settlement tank. The activated sludge tank and the settlement tank are 668 and 328 m^3, for the Montelepre WWTP, respectively, and 231 and 46 m^3, for Giardinello. The returned activated sludge recirculation for both plants is equal to the 100% of the dry weather flow. Additionally, the sludge retention times are 12 and 15 d^{-1}, for the Giardinello and Montelepre WWTP, respectively. The average mixed liquor suspended solids are 2.5 and 3 $kgVSS/m^3$, respectively. Rainfall was monitored by four rain gauges distributed over the basin (figure 2): the Montelepre rain gauge is operated by Palermo University, and is characterised by a 0.1 mm tipping bucket and a temporal resolution of 1 minute; the other three rain gauges are operated by the Regional Hydrological Service, and they are characterised by a 0.2 mm tipping bucket and a temporal resolution of 15 minutes. High resolution rainfall data were used for modelling urban catchment runoff generation while low resolution data were only used for the natural contributing catchment. The hydro-meteorological station (Nocella a Zucco) located at the catchment end is characterised by an ultra-sonic level gage operated by the Regional Hydrological Service, and has a temporal resolution of 15 minutes. Rainfall data for yearly maximum intensity events are available for all the raingauges since 1955 without any gap. The instruments were integrated by Palermo University by installing, for the quantity data, an area – velocity submerged probe that provides water level and velocity data with a 1 minute temporal resolution. An ultrasonic external probe was used to give a second water level measurement for validation, and as a backup in case the submerged probe failed; an automatic 24-bottle water quality sampler was used for water quality data collection. The monitoring campaign has been used for model calibration in the present condition. Details about the calibration process can be found in Freni et al. (2010).

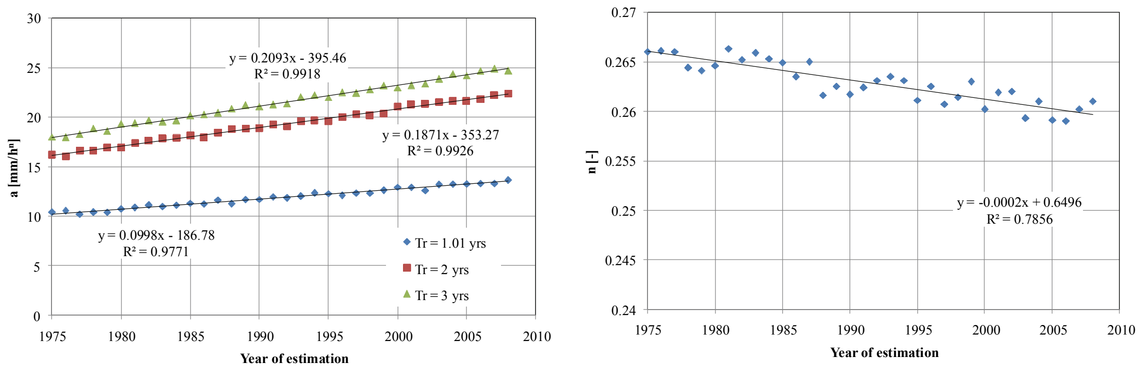
3 METHODOLOGY APPLICATION

The analysis of climatic and socio-economic drivers to global change and its impact on RWB environmental quality was carried out by means of scenario analysis. Four scenarios have been considered for evaluating the modifications in climate and socio economic conditions of the catchment:

- Past scenario set in 1985: in that year the two WWTP in the catchment were built and since then the urban drainage systems were not substantially modified apart from the construction of new pipes for serving new urban developments.
- Present scenario set in 2009: this scenario was used for model calibration and it represent the current situation of the catchment; the WWTPs work efficiently during dry weather but they are often surcharged in wet weather taking to the discharge of polluted waters to the RWB.
- Future scenarios: two future scenarios have been considered for analysing the mid-term impact (set at 2030) and the long-term impact (set at 2050).

Initially, climatic and socio – economic data have been collected and analysed in order to fit regression laws and obtain reliable values of the drivers in the mid- term and long-term scenarios.

Maximum annual rainfall intensities have been collected since 1955 and 20-year samples have been obtained by a moving temporal window in order to obtain different IDF curves for each raingauge and each year between 1975 and 2008. EV1 probability distributions have been fitted to each sample and the spatial average between raingauges has been obtained by applying Thiessen's polygons. Figure 4 shows the recoded data and the corresponding linear trends for the values of *a* and *n* in eq. 1 and eq. 2 spatially averaged over the catchment. The shape parameter *n* has been considered independent from return interval Tr because its variability for the considered values of Tr was lower than 1%.



(a) (b)

Figure 2. Linear trends of IDF parameters over time: (a), scale coefficient a; (b) shape coefficient n

Figure 2 clearly shows an increasing trend of IDF scale coefficient *a* demonstrating an increasing trend of maximum rainfall intensities over time. At the same time, the shape coefficient n shows a decreasing trend over time demonstrating that climate change impacts more short durations than longer ones. Table 1 shows the values of the IDF parameters for the four analysed scenarios.

	Past scenario (1985)	Present scenario (2009)	Mid-term future scenario (2030)	Long-term future scenario (2050)
a [mm/h^n] Tr=1.01 yrs	11.4	13.5	15.6	17.7
a [mm/h^n] Tr=2.0 yrs	18.1	22.2	26.3	30.4
a [mm/h^n] Tr=3.0 yrs	20.4	25.1	29.3	34.1
N	0.294	0.29	0.286	0.282

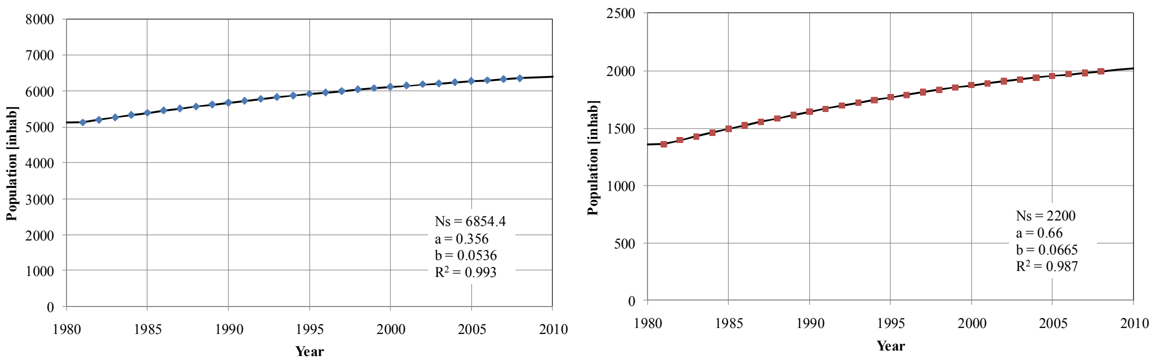
Table 1. Averaged IDF parameters for the different analysed scenarios and the considered return intervals Tr

Starting from the IDF curves, for the determination of the rainfall a synthetic hyetographs have been employed. The concentration time of the catchments has been calculated by analyzing both field data and results of simulation carried out during previous studies (Freni et al., 2009). More specifically, according to the analysis carried out, the time of concentration was approximately 40 min for the Montelepre catchment and 20 min for the Giardinello catchment. Hyetographs with Chicago shapes and return periods of 1, 1.5, and 2 years have been employed with aduration equal to the time of concentration of the single. A peak location defined as the ratio between peak time and total duration of the hyetograph of 0.5 has been employed for both catchments. The analysis aims to estimate the impact of climate change and urbanization on maximum polluting concentrations in the RWB and for this reason the use of synthetic rainfall events associated to a specific return interval may provide useful information on the increased frequencies of RWB polluting loads. When dealing with a single event simulation of stormwater quality, the dry period preceding the event must be specified. Usually, it is defined as the time interval between the event and the previous event that was able to wash off, in an effective way, the pollutants accumulated on the surface of the catchment. In fact, events with a rain volume lower than a threshold value (in this study 3 mm has been adopted) are usually not considered because they are mainly neutralized by initial losses and the residual runoff is not sufficient to produce relevant wash off. Usually, the longer the dry period, the higher the quantity of pollutants accumulated on the surface of the catchment; in the tests, the accumulation has been set to its asymptotic value that is substantially maximized after 30–40 days of dry weather to allow the consideration of the maximum effect in terms of water quality characteristics and impact on receiving water bodies. In the Mediterranean area, the annual maximum dry period frequently exceeds 50 days. For example, in the Palermo case, the data collected by National Italian Hydrographic Service years reveal that the maximum annual dry period has duration between 30 and 100 days with a mean value of 60 days. Anthropogenic data have been analysed by means of a similar regression approach:

annual data were collected since 1981 regarding demography, water demand and the extension of the urban area. The best regression law for population resulted to be logistic for both the urban areas and it can be written according to the following equation:

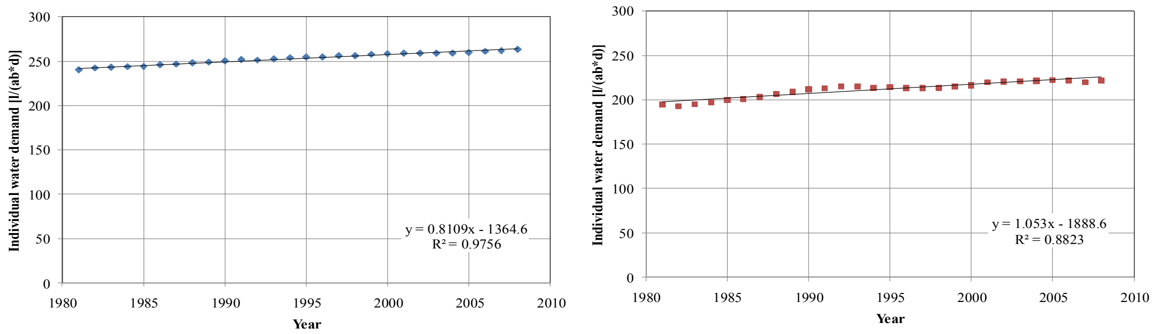
$$P(t) = \frac{N_s}{1 + a \cdot e^{-b(t-t_0)}} \qquad (3)$$

where Ns, a and b are calibration coefficients, t is the year of prediction and t0 is the initial year of the available dataset (1981). Recorded data and the calibrated regression laws are presented in figure 3 for both the urban areas with the calibrated values and the coefficient of determination R^2. Concerning the individual water demand and impervious area, the recorded data were best fitted with linear regression laws. In figure 4 and 5 the recorded data and the linear interpolation are reported.



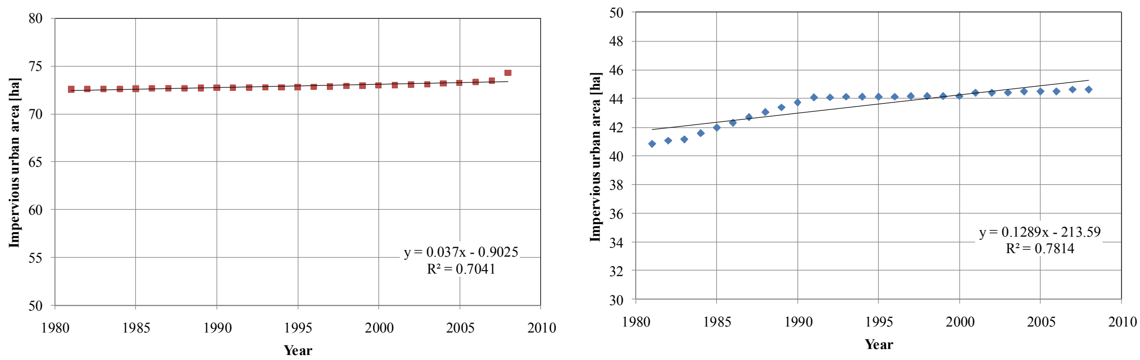
(a) (b)

Figure 3. Logistic trend of population of Montelepre (a) and Giardinello (b)



(a) (b)

Figure 4. Linear trend of individual water demand for Montelepre (a) and Giardinello (b)



(a) (b)

Figure 5. Linear trend of impervious area for Montelepre (a) and Giardinello (b)

The obtained regression laws allowed for estimating anthropogenic parameters for the selected scenarios and for the two urban areas analysed. The parameters are reported in Table 2.

	Past Scenario	Present Scenario	Mid-term future scenario	Long-term future scenario
Population [inhab] (Montelepre)	5285	6375	6691	6798
Impervious area [ha] (Montelepre)	72.13	73.46	74.24	74.98
Individual water demand [l/(ab*d)] (Montelepre)	248	262	269	272
Population [inhab] (Giardinello)	1510	2030	2148	2186
Impervious area [ha] (Giardinello)	42.5	45.1	48.1	50.5
Individual water demand [l/(ab*d)] (Giardinello)	200	228	250	269

Table 2. Predicted values for population, water demand and urban impervious area for the analysed scenarios

In order to evaluate the reliability of the predicted impact of climatic and anthropogenic variations on the quality of RWB, such impact was compared with the modelling uncertainty related to model parameters. Model parameters have been varied in ranges defined in previous studies (Freni et al., 2009). Parameter sets have been randomly drawn in the adopted ranges and 1000 simulations were run according to Monte Carlo approach. The uncertainty bands were obtained by means of the 5% and 95% quantiles of model predictions and their width was used as a qualitative expression of modelling uncertainty.

4 RESULTS ANALYSIS

Figure 6 reports the model results in terms of maximum peak flow at the most downstream river cross-section (Nocella a Zucco) for different years, return periods and uncertainty bands in terms of 5 and 95 percentile. The results revealed that generally there is an increase of the RWB discharge, regardless of the return periods, in accordance with the synthetic hyetographs evaluated by the hydrologic survey. Figure 6a shows the results for a return period of 1 year: the maximum peak flow shows basically a linear trend increasing up to 80% in 2050 of its values in 1985. Similarly, figure 6b and 6c shows an increasing positive trend for the maximum peak flow for a return period of 1.5 and 2 years, respectively. In terms of uncertainty, the confidence bands embrace the calibrated values and the average uncertainty band width is approximately 60% of the calibrated value. Further, uncertainty bands basically have the same linear trend as the calibrated values. The calibrated values are generally closer to the 95 percentile band. Figures 7 and 8 report the model results in terms of quality variables, i.e. maximum BOD and minimum DO concentration at Nocella a Zucco river cross section. The uncertainty bands are very wide and generally show a somewhat different behaviour respect to the quantity ones. In particular, the calibrated value curves, regardless the return period, are not linear. Nevertheless, the maximum BOD peak shows a general positive trend increasing up to 10% in 2050 of its values in 1985. Compared to the average slope of the maximum flow peak curve, the BOD one is less steep showing a less sensitivity of the quality processes to the climate change phenomena. Concerning the uncertainty bands the following considerations can be drawn:

- The uncertainty bands are very wide both for the BOD and for the DO.
- The uncertainty for the RWB BOD is approximately 200-300% of the DO.
- The average uncertainty bands for the BOD increase with time, not behaving a linear trend as in the case of the peak flow. This fact can be explained considering the different nature of the quality phenomena with respect to the quantity ones. In particular, the build up of the pollutant load and its propagation throughout the integrated system depends on many factors (e.g. solids accumulation in sewers), and some of them are not necessarily connected to the discharge values. Therefore a dissimilar behaviour between quantity and quality can be considered realistic.
- The processes may play a different role for the assessment of the maximum BOD peak in the river. This is the case for instance of WWTP settlement tank where the sludge blanket can or cannot rise causing a gross overflow of pollutants from the WWTP and consequent discharging in the RWB.

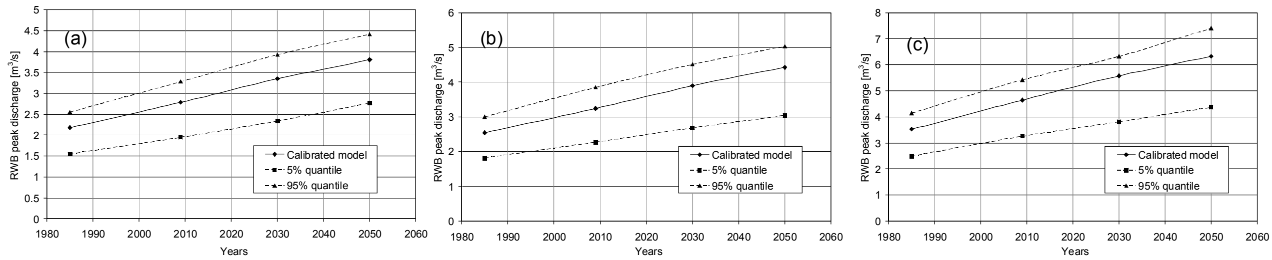


Figure 6. RWB peak discharges and uncertainty bands for different return periods: one year (a), 1.5 years (b) and 2 years (c)

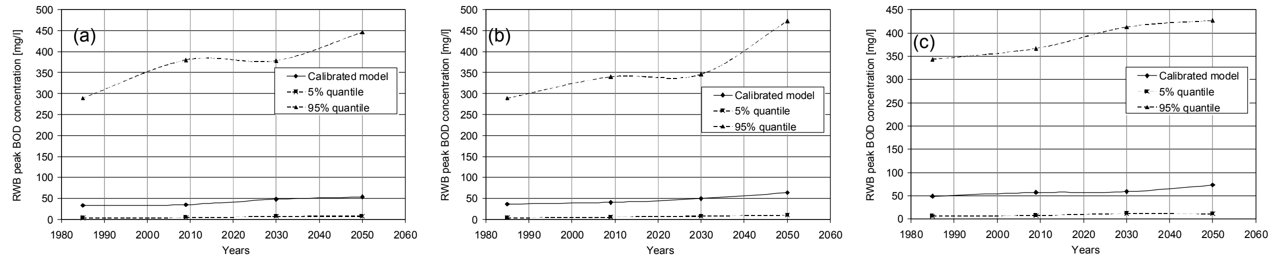


Figure 7. RWB BOD peak concentration and uncertainty bands for different return periods: one year (a), 1.5 years (b) and 2 years (c)

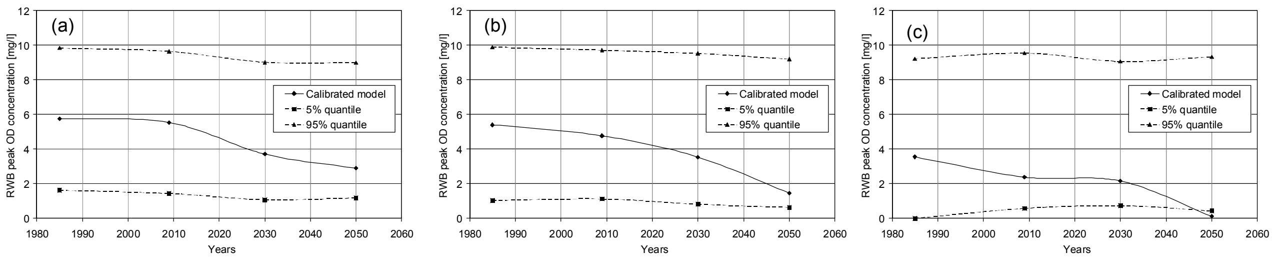


Figure 8. RWB OD peak concentration and uncertainty bands for different return periods: one year (a), 1.5 years (b) and 2 years (c)

5 CONCLUSIONS

In this study, we investigate anthropogenic and climate effects on receiving water body quality state by using an integrated urban drainage modelling approach. Further, as the modelling analysis is affected by inherent uncertainty due to model complexity and calibration, the analysis was performed considering the effect of such uncertainty on results reliability by means of Monte Carlo simulations. A preliminary analysis of the climate and anthropogenic trends was performed in order to assess the changes over time in the main input model variables. In particular four scenarios have been analyzed combining both climate and anthropogenic changes. The following considerations may be drawn:

- There is an increasing trend of the RWB discharge regardless of the return periods in accordance with the synthetic hyetographs evaluated by the hydrologic survey. In particular, there is a linear trend, resulting in RWB discharge increasing by 80% from 1985 to 2050.
- In terms of uncertainty, the confidence bands embrace the calibrated values and the average uncertainty band width is approximately 60% of the calibrated value. Further, uncertainty bands basically have the same linear trend of the calibrated values. The calibrated values are generally closer to the 95 percentile band.
- The maximum BOD peak shows a generally positive trend increasing up to 10% in 2050 of its values in 1985. Compared to the average slope of the maximum flow peak curve, the BOD trend is less steep, showing a lower sensitivity of the quality processes to the climate change phenomena.
- The uncertainty bands are very wide both for the BOD and for the DO and for the RWB BOD are approximately 200-300% of the DO values. This fact has the main consequence that the impact of climate change on water quality cannot be reliably assessed with the present modelling tools. Larger monitoring campaigns and more robust models may help reducing the uncertainty in

modelling estimation and thus increasing the confidence in model predictions and reducting uncertainty.

The results may help to inform planners and water specialists who advise them, to limit the impact of anthropogenic and climate changes because they can highlight the main drivers impacting water quality. The analysis also showed that further efforts are needed for increasing the reliability of modelling tools; otherwise, the model estimations will be affected by large errors reducing its applicability as a forecasting tool.

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